

BATTERIES OF THE FUTURE: POWERING THE HYPERLOOP TRANSPORTATION SYSTEM*

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Abstract

Several energy storage options are evaluated for the Hyperloop's internal and external energy storage requirements. The following technologies are considered for both applications: LightSail Energy, Vanadium Redox Batteries, Flywheel technology, Lithium-Ion Batteries, and Lead-Acid Batteries. Lithium-ion batteries are recommended for the Hyperloop capsule's interior energy storage system and LightSail Energy is recommended for application to the Hyperloop's external solar energy storage system, as determined using Pugh Matrix evaluation methods.

Introduction

In 2008, California approved funds to finance the "California High Speed Rail," which would connect northern and southern California between San Francisco and Los Angeles, and later expand into Sacramento and San Diego. A high speed rail, however, does not reduce trip times or cost compared to existing modes of transportation. Elon Musk, an American entrepreneur and billionaire-investor, has proposed a Hyperloop transportation system as an alternative to a high-speed train. The Hyperloop contains three main structural components: a capsule, tube, and propulsion system. Carrying 28 passengers each, the capsules are supported by air-bearing skis that rely on an onboard compressor to create aerodynamic lift. The steel tubes are supported by pylons and covered with solar panels to power the system. Finally, the propulsion system consists of magnetic linear accelerators outside the tube, which transfer momentum to the capsules via onboard rotors (Musk).

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One area of the Hyperloop that needs further exploration is the onboard energy storage system. A key component of this system is an electric compressor fan, which moves high-pressure air from the front to rear of the capsule, while also supplying air to the air-bearing skis that support the capsule's weight throughout the trip. An energy storage system is needed to power this onboard compressor (Musk). Altogether, this paper analyzes five potential energy storage systems for the Hyperloop: Vanadium Redox flow batteries, Beacon Flywheel technology, LightSail Energy, Lead-Acid batteries, and Lithium Ion batteries. The advantages and disadvantages of all the energy storage options are discussed in detail below. To compare these technologies, a Pugh Matrix was created with the chosen design criteria of efficiency, safety, cost, reliability, size, and weight. From the Pugh Matrix, the Lithium Ion battery was selected as the most viable energy storage option.

In addition to evaluating the internal power demands, the external power demands were also assessed for the Hyperloop's magnetic linear accelerators. We analyzed the external power system in order to make a more complete energy storage recommendation for the Hyperloop and to analyze if some of the unfeasible options for the interior system were viable for the external system, as discussed below. The energy storage alternatives used to evaluate the exterior system were the same as those used for the interior system. A modified set of design criteria was used to create an additional Pugh Matrix to compare exterior energy alternatives, and LightSail Energy was chosen as the most viable solution.

Design Criteria

Efficiency

The energy storage capacity and performance was evaluated for the overall efficiency of each technology by using the specific energy (in energy output per unit mass) and the overall mechanical efficiency of each technology, as reported by its developers. Efficiency is the key design criterion used to compare the power abilities of each technology, and while there was no minimal specific energy or efficiency requirement set, each system was scaled to match the power rating of 330 kW for internal energy storage, or 37 MW for external energy storage (Ap. 2.4, General, Kenwood, How).

For the batteries evaluated, power is assumed to be linearly related to the weight of the battery since the voltage of a galvanic cell battery is the sum of the voltages of each individual cell, and power is directly related to voltage. In the Hyperloop, the batteries were scaled to meet the energy requirement. Thus, the battery can sustain a power level greater than necessary, but any level of power can be drawn from a battery, provided it does not exceed the safe limit.

Safety

When establishing the safety design criterion, temperature and hazardous material were the two main factors considered. The temperature range chosen was -6.6 degrees Celsius to 48 degrees Celsius, based on the temperature range of California (The Weather Channel). There should also be no mechanical or chemical hazards associated with the system. Additionally, the battery should be able to withstand pressures ranging from 100 Pa (inside the tube) to 101,325 Pa (inside the capsule) if there is cabin pressure loss. Considering the possibility of earthquakes in California, the system should also be shock-resistant. Finally, the system should allow for reserve power storage in case of emergencies regarding travel such as cabin pressure loss (Musk). The safety and efficiency of the technologies can be compared in Tables 3 and 4 (Ap. 1A).

Cost

After calculations, the determined budget of the internal energy storage system was \$120,000 per capsule (O'Brien, Ap. 2.2). We assumed, when scaling each technology that the cost would scale linearly with the candidate system sizes. Although the cost of the energy storage system is orders of magnitude smaller than the total proposed cost of the Hyperloop system, it is still necessary to compare each of these technologies in terms of cost. The cost comparisons performed in our study are summarized in Figures 3 and 4 (Ap. 1B).

Reliability

An important consideration for each system was its cycle life and durability, otherwise represented by reliability. We assumed that operation in the Hyperloop is representative of normal advertised operation for these candidate technologies when discussing each alternative's cycle life and longevity.

Size

Assuming a triangular prism for any non-cabin volume, the volume available for internal energy storage

was determined to be 6.4 m^3 (Musk, Ap. 2.3). The capsule was modeled after a government-standardized single level passenger rail car (NIST, Ap. 2.3). For the exterior system, only the lateral area, or footprint, was considered. The size comparisons between each technology are summarized in Figures 2 and 5 (Ap. 1B).

Weight

Because of the sensitive design of the suspended capsule system, the weight of the energy storage system was an important constraint. When analyzing our energy storage options, the maximum weight allowed was 1500 kg, which was the weight Musk allotted to provide onboard power for 45 minutes. The weights were calculated by using the specific energy (energy per unit mass) of each system, and then scaled to fit the energy and power requirements. The energy storage capacity was also accounted for in this design criteria through the specific energy densities. The red line in Figure 1 (Ap. 1B) allows comparison of each system's weight with the maximum weight as determined by Musk.

Energy Storage Alternatives

Vanadium Redox Batteries

The first energy storage system considered was the vanadium redox battery (VRBs). Redox flow batteries (RFBs) are batteries that store energy in two independent tanks separated by a cell stack. This separation allows the battery to be easily scaled to fit both energy and power requirements. The greater the volume of the storage tanks, the more energy is stored in the system. Likewise, more cell stacks is equivalent to a greater power capacity (Industrial). Other types of RFBs include iron/chromium and zinc/bromide (Wang).

VRBs are unique in that both tanks store energy in different forms of a single element: vanadium (see Table 8 for scaling bases, Ap. 6 for all technical evaluation calculations and discussion). Because there is only one element, both tanks have the same liquid chemistries and there is no risk of electrolyte cross-contamination. The electrolyte is also reusable, not flammable, contains no heavy metals, and runs at room temperature ($10\text{--}40^\circ\text{C}$) (Storage).

Problems with current VRBs include low energy densities ($\sim 25 \text{ Wh/kg}$) and a small operating temperature range (from 10 to 40°C). Recent research performed at the Pacific Northwest National Laboratory has made significant progress towards correcting these problems. By replacing the sulfuric acid electrolyte with a sulfate and chloride mixture, scientists have increased the energy capacity of VRBs by as much as 70% to 42.5 Wh/kg . They have also extended the operating temperature range by 83% so they now run from -5 to 50°C (Wang). An additional problem found when evaluating VRBs for the Hyperloop system was that the size and weights of VRBs are much heavier and larger than those specified in the design criteria. After taking into account both the storage tanks and the cell stacks, the total weight of the storage system would be 17,799 kg and the total size would be 62.5 m^3 . These numbers indicate that a vanadium redox flow battery would not be an ideal candidate for the onboard power system. VRBs would, however, be a good energy storage candidate if the system were not restricted by size or weight (Ap. 6, Table 8 Ap. 1A).

Flywheel

Flywheel technology is a mechanical energy storage system that uses a spinning wheel to store energy in the form of kinetic energy (Bolund). The mechanism is several centuries old, however in the 20th century, improvements in technology spurred a renewed interest, with commercial ventures seeking to create a market for the device. The concept behind storing energy in a flywheel is simple. A power source operates a motor that spins a wheel at very high speeds, then the wheel slows down as it delivers the energy back through a generator. Recently, advancements in the design materials have allowed the flywheel to spin at much faster speeds, increasing the energy capacity of the wheel, while magnetic bearing systems minimize energy loss due to friction (Hebner).

The flywheel system sold by Beacon Power, LLC was selected as the baseline for the analysis (see Table 6 Ap. 1A for scaling bases, Ap. 4 for technical evaluation calculations and discussion, Ap. 1C for diagrams). Other potential flywheel systems are still in development and may not reach a commercialization stage until after the Hyperloop system is built. Beacon Power provides a flywheel system, which is currently being used in a 20 MW plant in Stephentown, NY (Beacon Power). The company offers clear technical specifications (Table 6 Ap. 1A), which were used to scale the flywheel system to match the specifications of both the interior and exterior energy storage systems.

Beacon Power Flywheels offer no emission and require very little maintenance with a lifetime of 100,000

cycles over a 20 year design life. Furthermore, there is no degradation with depth of discharge, cycle duty, charging rate, time or temperature (Flywheel Energy). The disadvantages of the technology include a low energy density compared to traditional lithium-ion and lead-acid batteries and a potential safety concern due to the high speeds of the flywheel. Because of these disadvantages, flywheels would not be capable of fitting within the current design criteria of the Hyperloop. The size and weight for each system hinders its replacement at each stop, therefore the flywheels would be need to be charged within the capsule.

Lead-Acid Batteries

The next technology considered was the lead-acid battery. The Power-Sonic PDC 122000 deep-cycle rechargeable battery provided specifications that allowed for the calculation of the much larger battery in the Hyperloop (PDC 122000). A lead-acid battery uses the potential created by a galvanic (or voltaic) cell, which consists of its two electrodes lead and lead oxide, bathed in a sulfuric acid electrolyte solution, to store energy.

The lead-acid battery is used most often in automobiles to start the engine (Omar). This means that a relatively large power surge is required for a short period of time, so energy storage capacity is not a concern, making the cheap lead acid battery ideal for this application (EPRI, see Ap. 7 for all technical evaluation calculations and discussion), Table 9). Safety concerns for the lead-acid battery include the fact that lead and sulfuric acid are highly corrosive and hazardous. The disposal of lead, itself, is a well-established industry (Material Safety Data Sheet). Another danger is the electrolysis of water, which produces hydrogen gas that quickly exerts large pressures within the system. In general, lead-acid performs best when only a little of its charge is used up each time (Robert). Lifetime of a lead-acid battery is generally about 500 cycles at 50% discharge and 200 cycles at 100% discharge (Battery). Shelf life is also an important factor. After 6 months, only about 80% of nominal charge remains (PDC 122000).

This battery system is very flexible in determining sizing and weight to fit the power requirements, and it often has very high specific energies (Martha, Ap. 7). Due to lead-acid batteries' limited life cycle and rechargeability, they are not considered to be a very reliable energy source.

LightSail Energy

LightSail Energy is a Berkeley-based start-up corporation that recently formed around a single compressed-air energy storage (CAES) concept for an application to electric vehicles that is cleaner than standard lithium-ion batteries (Fong). Today, they have several patents published for thermodynamically efficient CAES systems that will one day be applicable to urban power sources, including main power grids which utilize a simple piston-compression system to heat air (for thermal energy storage). The key feature of LightSail's CAES design is the addition of a water storage tank and nozzle apparatus that allows for the injection of water vapor droplets into the piston chamber during isothermal compression (LightSail). Because water has a much higher heat capacity than air, according to LightSail, the ability of the CAES system to retain energy greatly increases, as the process is "reversible" (Shobana). The creator of the technology has stated that the water droplets allow the compression storage cycle to be practically reversible - the water droplets serve as an infinite number of heat reservoirs for the air to exchange heat with, which allows for a microscopically reversible isothermal process to occur (Fong, Crooks).

LightSail Energy's CAES system was evaluated against our five design criteria for the interior energy needs of the Hyperloop capsule to reveal limited feasibility as a proper choice. For efficiency, LightSail has stated that they can produce 80% round-trip thermal efficiency, which we assumed to mean the total thermal efficiency of the air compression and expansion, for a target net mechanical or overall efficiency of roughly 75%. The scaling was performed using the stated, strict scale factor of 1.5' by 1' by .75' (Fong, Ap. 3 for all technical evaluation calculations and discussion, and Table 5 Ap. 1A for scaling bases). Despite its inherent safety with no hazardous materials, the LightSail system is heavy, follows strict box-type scaling requirements, and has limited viability for application inside the Hyperloop capsule. Through evaluation of the exterior power system, however, LightSail has shown strong promise as an energy storage system for the linear accelerators (Tables 2 and 4 Ap. 1A). Because of a lack of weight or size constraints for the external system, the primary factors holding it back for internal energy storage, LightSail was the chosen method for the outside energy storage system.

Lithium-Ion Batteries

Lithium ion batteries are rechargeable batteries that are used in many consumer electronics as well as for large electric vehicles and hybrids. The batteries have three parts, an anode (lithium cobalt oxide), cathode (carbon), and an electrolyte, which participate in the electrochemical reaction. The lithium ions migrate towards and away from the electrodes, and in a closed circuit work can be extracted from the electrons. (Wakihara).

The model examined for use in the Hyperloop is the Panasonic 18650 3.1ah Lithium Ion battery (See Ap. 1C, Diagram 3). This battery is usually used in small-scale electronics however Tesla Motors uses this battery in series to power their Tesla Model S electric cars (Demorro). The batteries have a relatively high energy density allowing them to serve as a stable source of energy for the Hyperloop capsules if used in series. The weight required to support the needs of the Hyperloop capsules is relatively low and the batteries also take up a small volume of the capsule (See Ap. 5A for all technical evaluation calculations and discussion). Furthermore there is no battery memory or scheduled cycling required, prolonging the battery's life. Self-discharge of the battery is less than half when compared to traditional nickel-cadmium batteries, while the cell voltage is almost twice that of the nickel-cadmium (Panasonic).

There are some limitations with using the lithium ion batteries. The batteries can last for about 300 cycles at 80% discharge, and in many cases capacity deterioration is noticeable after one year, even when the battery is not in use. Lithium-ion batteries are fragile and must be carefully monitored to make sure the battery doesn't drop too low on discharge. Cell temperature also needs to be in check, which is why a coolant system is used to prevent temperature extremes. The batteries can also be dangerous since they usually contain a flammable electrolyte and are also kept pressurized. However, Panasonic batteries include a gas discharge valve that releases internal gas in the case of overheating.

Overall, the advantages of lithium-ion batteries outweigh the disadvantages, making the batteries a promising technology for the use in the Hyperloop passenger capsule.

Methods and Evaluation

To find the best energy storage technology for the Hyperloop capsule, design criteria were developed, as described above and the different types of technologies were compared. Initially eight different technologies were considered as potential energy sources. These technologies include, LightSail Energy CAES system, conventional Lead-Acid batteries, Panasonic Lithium-Ion batteries, Vanadium Redox Flow system, Beacon Power Flywheel arrays, Superconducting Magnetic Energy Storage Systems (SMESs), Velkess kinetic flywheel systems, and carbon nanotube (CNT) supported lithium-ion systems. However, since some of these technologies were in early stages of development, it was decided that the research for an alternative energy source would be limited to the LightSail Energy CAES system, conventional Lead-Acid batteries, Tesla's Lithium-Ion batteries, Vanadium Redox Flow system and Beacon Power Flywheel arrays.

In developing the Pugh matrix, every technology was compared against the different design criteria and given a score ranging from 1 through 5, where 5 indicated that the technology was the best possible option when compared to the design criteria or when compared to the other technologies. Furthermore, in order to develop the weightage of every design criteria, each one of the 6 design criteria was given a score of between 1 - 6 by all the group members where 1 represented the most important one and 6 the least important design criteria. These design criteria were then weighted appropriately in order to ensure that the weighted average of the different technologies significantly differ. Keeping this in mind, the different design criteria were weighted as shown - Efficiency - 30%, Safety - 20%, Cost - 15%, Reliability - 15%, Size - 10%, and Weight - 10%. Finally, a weighted score was calculated for every design criterion. This score indicated which technology would be the most appropriate as an internal energy source. (See Ap. 1A). The same overall evaluation procedures were performed for the exterior energy storage system, to give a set of modified design criteria of Efficiency - 30%, Safety - 20%, Cost - 15%, Footprint (Area) - 15%, Reliability - 20% (see Ap. 1B).

The comparisons used to make the final proposals for the interior and exterior systems are summarized in the figures shown in Appendix 1B, but formalized in the Pugh Matrices shown in Tables 1 and 2. For the interior system, the Flywheel, Vanadium, and LightSail were ruled out mostly due to size and weight constraints (Figs. 1, 2 Ap. 1B), whereas lead-acid batteries were deemed less appropriate than lithium-ion batteries due to lower specific energy and poor reliability (Tables 1 and 3 Ap. 1A). For the exterior system,

the vanadium and flywheel systems were ruled out due to significantly greater environmental impact and footprint area, respectively (Figure 5 Ap. 1B), and the lithium-ion and lead-acid battery systems were slightly more expensive and less reliable than the LightSail system, which was superior in safety and overall footprint (Figure 4 Ap. 1B, Tables 2 and 4 Ap. 1A).

Analysis Limitations and Alternatives

The most significant limiting assumption is that the large battery for the capsule is linearly scalable from smaller commercial batteries. Using specifications from actual batteries in production, the smaller batteries are linearly scaled to meet design criteria. Furthermore, a constant nominal voltage value was assumed, not accounting for change in state of charge that could occur over the life of the battery or even during one discharge cycle. Commercial data is used which may be different from what can be used in the Hyperloop. Because there were no explicit references to dimensions of the Hyperloop capsule, a final assumption was made that the capsule dimensions were roughly the same as those from a single train car.

In addition to the passenger capsules, energy storage for the linear accelerator was explored using the same methods of evaluation and technology considered for inside the capsules. This was done because some of the technologies performed better when a higher power requirement (see Ap 2.2.) such as the accelerator, was required, as well as when size and weight constraints were not as important. A separate “outside” Pugh Matrix was made in order to evaluate the new criteria (see Ap. 1A Table 2 and 4).

Final Recommendations

After reviewing the various technologies, lithium-ion batteries are found to be the most suitable energy source for the passenger capsule (See Ap. 1B Figures). The Panasonic 18650 batteries have the highest energy density among all the different types of energy sources evaluated, making them the most functional for the capsule, a limited size transportation system. Furthermore, since the battery type used is similar to the one used by Tesla’s cars, large scale production and manufacturing of the batteries would not be a problem. The batteries can be cooled through the coolant systems provided by the compressor motor, ensuring that they do not cross the maximum or minimum temperature boundary (Musk). With additional safety features integrated in the battery, the risk associated with battery failure would be minimal (Panasonic). Overheating is also prevented by simply adding more batteries to reduce the power drawn per battery, keeping them at a safe power usage. The only current drawback is that the batteries would need to be replaced roughly every 300 cycles, which is about every 10 days per set, costing roughly 3.1 million dollars per set, per year (See Ap. 5A). When considering that there will be multiple capsules running, the costs of replacing the batteries begins to add up. However, lithium-ion batteries benefits still significantly outweigh the cost factor. Battery technology is constantly improving, so there is no doubt that the cycle time will increase over the next few years. Even Tesla recently announced a new patent on improving the range of Lithium batteries (Stewart). Lastly, as far as lithium reserves are concerned, a study recently released by the University of Michigan estimated global lithium resources to be about 39 million tons, and assured that even in the highest demand scenario, there is enough lithium to last till the turn of the century (Gruber 775). Although lithium resources are not in question, lithium itself is a heavy metal, therefore a biohazard, and must be discarded appropriately. With lithium batteries powering everything from phones to electric vehicles, it makes sense that they would be the best option for the Hyperloop capsules.

Additionally, when considering the overall energy storage systems for the Hyperloop, LightSail Energy is strongly recommended for application and scaling to the 37 MW energy storage system for the linear accelerators, located outside of the capsules themselves. Since the linear accelerator and its accessory components are not strictly bound by the volume constraints of the Hyperloop capsule and tube, only the footprint in surface area is necessary for consideration as a design consideration, and no upper size value existed for the outside system. When scaled to four 10 MW systems, we found that LightSail Energy gives the most cost-effective solution for the accelerator compared to the others (when considering the replacement costs of the conventional and lithium batteries) (see Figure 4 Ap. 1B). As Elon Musk suggested, LightSail Energy would provide an environmentally friendly, safe, and highly efficient energy storage system for the Hyperloop stations’ accelerators, and we recommend them here as well (Musk).

Conclusion

In this project, our main objective was to explore different types of technologies that could be used to

power the compressor motor and meet energy requirements of the Hyperloop passenger capsules. The technologies assessed were Vanadium Redox Batteries, Panasonic Lithium-Ion Batteries, the Beacon Flywheel, Lightsail, and Lithium-Ion Batteries. These technologies were then evaluated through a Pugh Matrix on certain design criteria: cost, weight, size, efficiency, reliability, and safety. Looking at the results suggested from the Pugh Matrix, lithium-ion batteries exceeded all other technologies for the capsule energy source. In addition to the capsules, energy storage for the linear accelerator was also analyzed using a similar Pugh matrix, and Lightsail was found to be the most effective technology. Thus using lithium-ion batteries in the capsules and LightSail to power the accelerators could serve as a formidable combination in making the Hyperloop design become a reality.

Please see attached Appendices for the supporting calculations, detailed discussions, and all Works Cited in the module's downloads section.